The effects of radiation and creep on viscoelastic damping materials

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ABSTRACT

The Advanced Photon Source (APS), under construction at Argonne National Laboratory (ANL), requires precise alignment of several large magnets. Submicron vibratory displacements of the magnets can degrade the performance of this important facility. Viscoelastic materials (VEM) have been shown to be effective in the control of the vibration of these magnets. Damping pads, placed under the magnet support structures in the APS storage ring, use thin layers of VEM. These soft VEM layers are subject to both high-energy radiation environment and continuous through-the-thickness compressive loads. Material experiments were conducted to answer concerns over the long term effects of the radiation environment and creep in the viscoelastic damping layers. The effects of exposure to radiation as high as 10^8 rad on the complex modulus were measured. Through-the-thickness creep displacements of VEM thin layers subjected to static loads of 50 psi were measured. Creep tests were conducted at elevated temperatures. Time-temperature equivalence principles were used to project creep displacements at room temperatures over several years. These damping material measurements should be of interest to vibration control engineers working with a variety of applications of fields ranging from aerospace to industrial machinery.

Keywords: viscoelastic materials, damping, creep, radiation, complex modulus, loss factor

1. BACKGROUND

The Advanced Photon Source (APS), under construction at Argonne National Laboratory (ANL), will produce extremely brilliant x-rays for a broad range of materials, chemistry and medical research. In this facility, positrons are produced and accelerated to energy levels of 7-Gev. These positrons are then injected into a 1040 meter circumference storage ring where they circulate for periods of up to 18 hours. This beam of positrons emits high energy x-rays as it is positioned and controlled by large electromagnets. The several magnets are mounted on each of 200 girder assemblies. A typical girder assembly, illustrated on figure 1, weighs 7,500 Kg. A critical performance parameter of the APS is vibration of the quadrupole magnets in the storage ring. Very small vibratory displacements, in the submicron range, can distort the positron closed orbit and degrade the performance of the facility. Resonances of the magnet supporting structures can be excited by low level ground vibration. Vibration damping pads have been shown to be effective in reducing the vibration of the magnets in the APS storage ring. These pads consist of three layers of steel approximately 8.5 by 12 inches by .070" thick bonded with two .004" to .007" layers of viscoelastic pressure sensitive adhesives (PSA) as shown in figure 2. The performance of these devices was optimized by experimentally determining the dynamic displacements and analyzing the dynamic strains induced in the viscoelastic layers. Several candidate viscoelastic damping materials were investigated with consideration of their complex modulus at the temperature and frequencies expected in service. Damping in the most critical mode, at approximately 12 Hz, was increased by a factor of about 25 with the appropriate choice of materials and configuration. Since these soft VEM layers will be subject to both high-energy radiation and continuous through-the-thickness compressive loads, investigations were conducted into the effects of radiation and creep.

2. RADIATION EFFECTS

Although it was qualitatively understood that high energy radiation could affect the damping properties of these materials, little quantitative data was available to predict performance in the APS environment. This investigation was undertaken to determine the effects of high energy radiation on the damping properties of VEM considered for use in the APS storage ring. Materials investigated included three acrylic pressure sensitive adhesives (3M ISD 112, Anatrol AN217, and Anatrol AN218), a thermoset phenolic-rubber (Norwood PM220), and a fluoro-silicone elastomer (Furon CE 5530C). Baseline damping properties of each VEM sample were characterized by measuring complex modulus, as a function of temperature and frequency, before exposure to high energy radiation. Samples were then exposed to gamma radiation, using a Cobalt 60 source, to obtain radiation doses ranging from 1.13 x 10^5 to 1.34 x 10^8 rad.

2.1 Complex modulus measurements

Materials were characterized by Roush Anatrol using the vibrating beam technique following ASTM Standard E-756. The dynamic material properties of viscoelastic materials were calculated from measurements made on sandwich (polymer/steel) cantilever beams, with the VEM dynamically deformed in shear. Fourth order laminated beam theory was used to calculate the VEM dynamic modulus and material loss factor properties from the specimen response data [1]. The effects of frequency were determined by evaluating material properties for several bending modes. Temperature effects were determined by placing the test fixture inside an environmental chamber, as shown in figure 3, and repeating the measurements for selected temperatures. These tests used steel base beams measuring about 0.0625" thick, 0.5" wide, and having free length of 10". The flexural rigidity of each base beam was measured as a function of temperature before specimen buildup. Sandwich specimens were fabricated from the base beams and VEM material as shown in figure 4. Beam specimens were mounted in a test apparatus to provide a boundary condition at the root end that was essentially clamped. Random noise excitation was provided at the free end of the beam using a non-contacting magnetic exciter. The response of the beam was measured with a piezoelectric crystal mounted near the root of the beam. Transducers were extremely light or of the non-contacting variety to minimize their effects on resonant frequencies and extraneous sources of damping. The frequency response of the beam was monitored over a frequency range including the second, third, fourth, fifth, and sixth bending modes. A frequency range of about 100 Hz to 3500 Hz was covered. Resonance frequency and loss factor values were measured using zoom transform measurements at each bending mode of interest. The temperature-frequency superposition principle [2] was applied to collapse data taken at various temperatures and frequencies to master graphs of the shear storage modulus and loss factor. Data was plotted as nomograms that show measured properties of each VEM sample, under baseline conditions and after exposure to different levels of radiation, as a function of reduced frequency f α_T. The shift factor function α_T used to collapse the data to master curves, was based on the Arrhenius relationship.

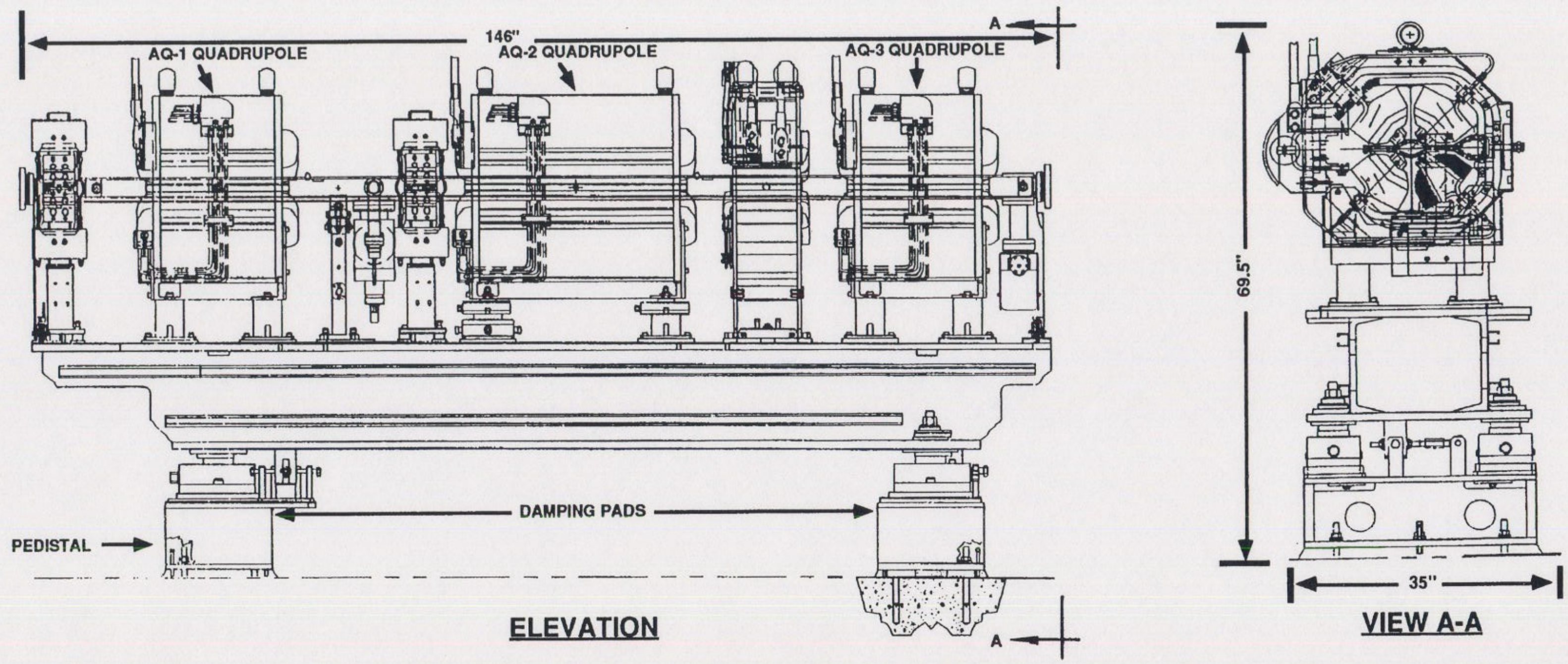

FIGURE 1: TYPICAL APS STORAGE RING GIRDER ASSEMBLY

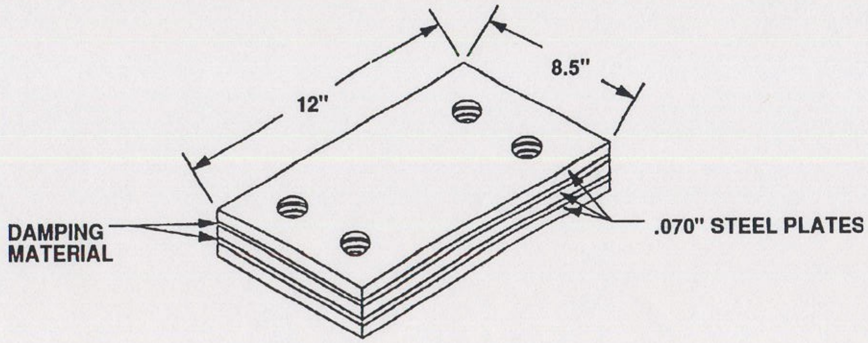

FIGURE 2: LAMINATED DAMPING PAD

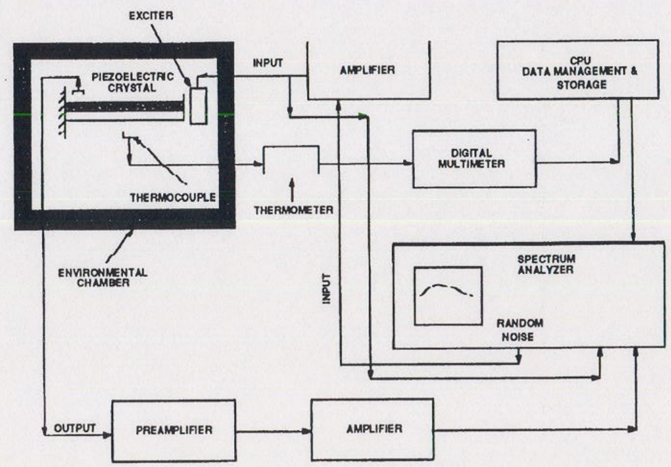

FIGURE 3: BLOCK DIAGRAM OF LABORATORY TEST SET-UP FOR VIBRATING BEAM TESTS

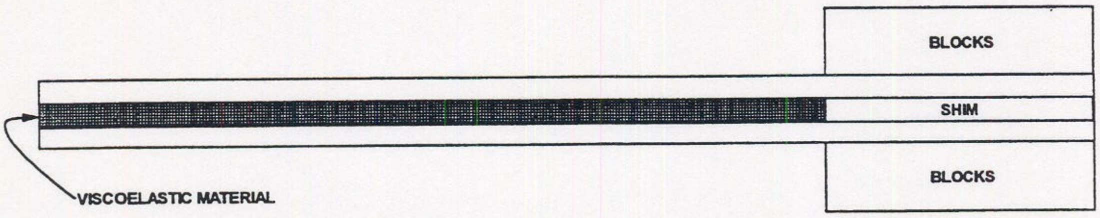

FIGURE 4: Sandwich test specimen for vibrating beam tests

2.2 Radiation exposure

The sandwich beam test specimens were exposed to high energy gamma radiation from Cobalt 60 by Argonne National Laboratory. Radiation flux (rad/hr) was measured at midspan and near each end of the specimens. These measurements were made on the front side (nearest to the source) and back side of the specimens. The radiation flux at the midplane on the VEM layer was calculated as the mean of average of the front side measurements and the average of the back side measurements. Total radiation dose for each test was calculated as the product of the radiation flux and the time of the exposure. Radiation exposures up to 1.54×10^7 rad were conducted at a flux of approximately 6×10^4 rad/hr. Doses of 1.34×10^8 rad were acquired at a rate of 4.15×10^5 rad/hr. The effects of elevated temperature and irradiation can be synergistic. The possibility that the higher radiation flux might induce higher temperatures and create greater damage in the specimen was checked by exposing some specimens to 1.07×10^7 rad at the higher flux. VEM properties of specimens exposed to 1.54×10^7 rad at the lower radiation flux were compared with the specimens receiving a dose of 1.07×10^7 rad at the higher flux. No significant difference was noted in the specimens tested at the different flux levels used in these tests.

2.3 Radiation results

Figure 5 shows the typical discrete experimental data superimposed with an analytical curve fit of the data. Nomograms for Anatrol AN217, and Norwood 220 used data from tests of two beams with different VEM thicknesses to fully populate the temperature-frequency domain, at each level of radiation dose. Figures 6 and 7 show examples of sample to sample variations for two different materials (3M ISD 112, and Norwood PM 220.) Comparisons between baseline properties for each material and properties measured after various levels of radiation exposure are shown in Figures 8-12

Radiation effects on polymers can be a complex combination of scission of long molecular chains and crosslinking [3]. Scission creates a reduction in modulus and crosslinking increases the modulus, particularly in the rubbery (soft) temperature region. Only minor changes were noted in the measured shear modulus and loss factor of all materials that received radiation doses of 1.54×10^7 rad or less. Figure 8 shows that 3M ISD 112 exhibited up to about 20 percent increase in the rubbery region modulus, and no change in peak loss factor after exposure to 1.54×10^7 rad. Other materials with radiation doses of 1.54×10^7 rad or less showed either small increases or small decreases in modulus. These changes were only slightly higher than sample to sample variations in baseline data.

The phenolic-rubber (Norwood PM220) and one acrylic adhesive (3M ISD 112) received doses of 1.34×10^8 rad. The modulus of Norwood PM220 [figure 12] was increased by a factor of about ten in the transition temperature region. Peak loss factor was decreased by a factor of about two. 3M ISD 112 showed a modulus increase of a factor of about three in the transition temperature region and a modulus increase by a factor over ten in the rubbery region [figure 8]. No change was noted in peak loss factor, but loss factor in the rubbery region was decreased by a factor of about ten. These changes in properties are typical of increased crosslinking.

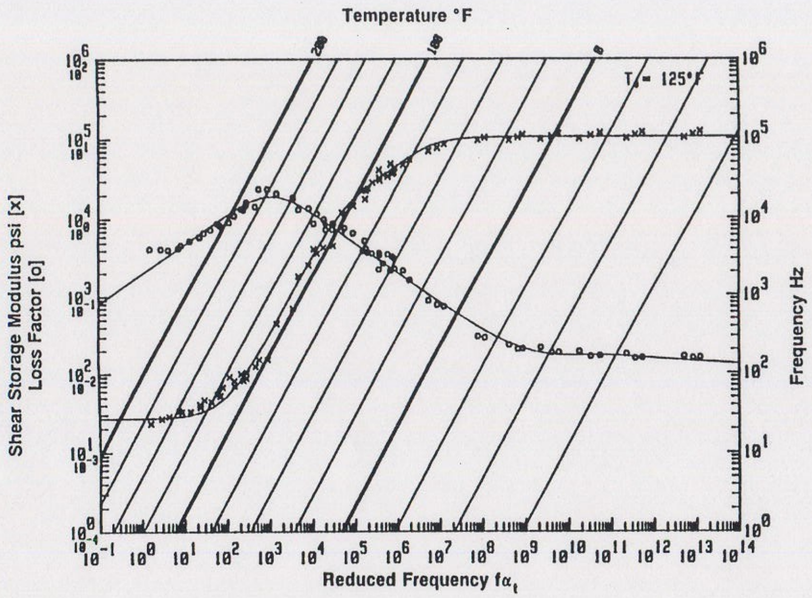

Figure 5. NORWOOD PM 220 Baseline Measurements

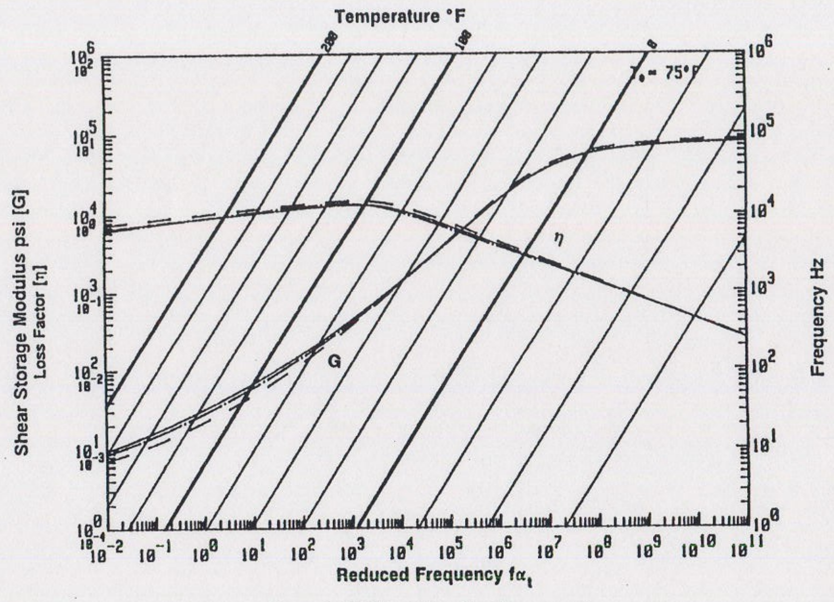

Figure 6. 3M ISD 112 Baseline Measurements

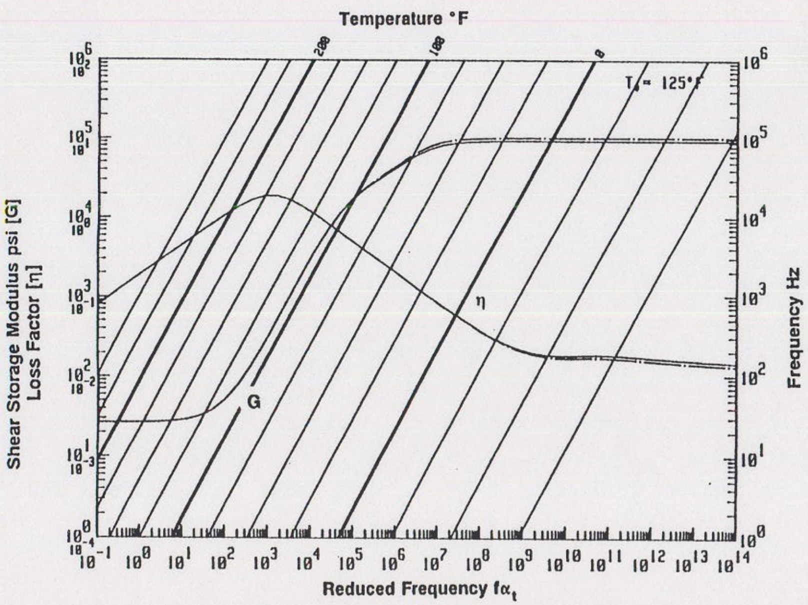

Figure 7. NORWOOD PM 220 Baseline Measurements

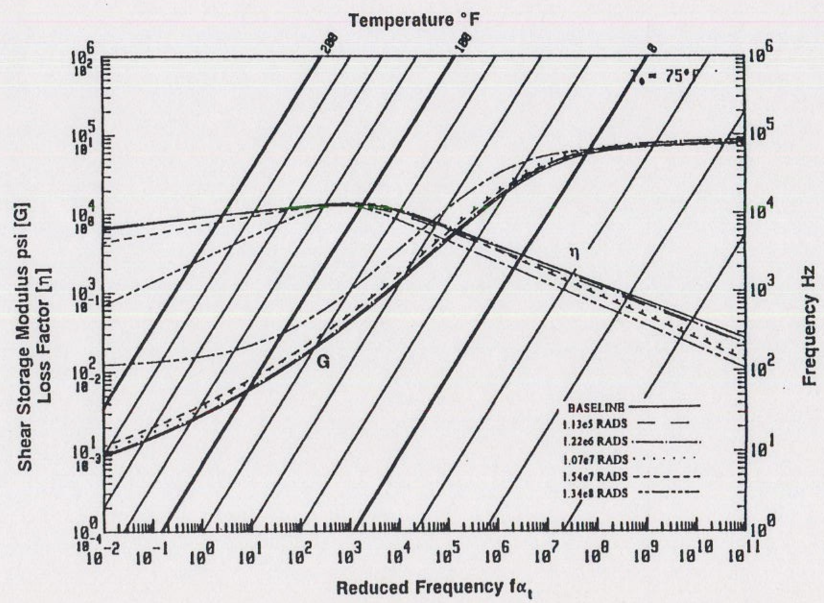

Figure 8. 3M ISD 112 Radiation Effects

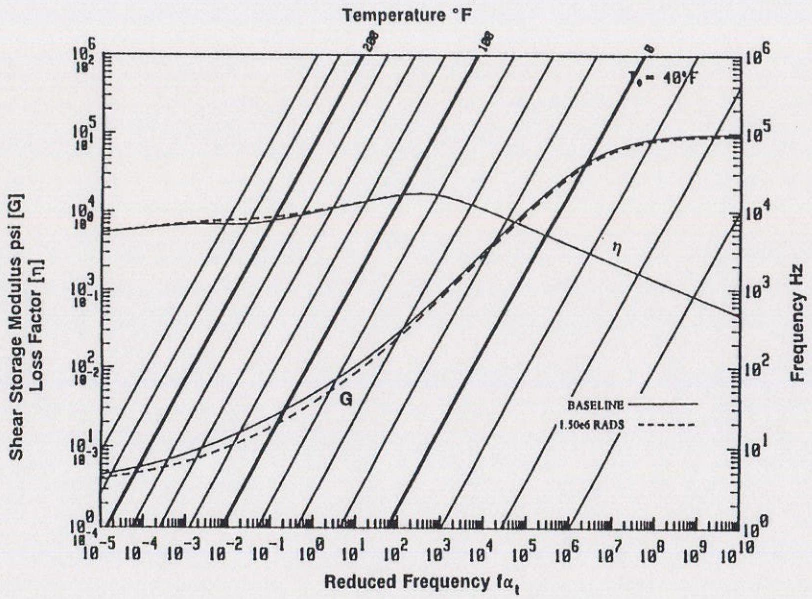

Figure 9. Anatrol AN 217 Radiation Effects

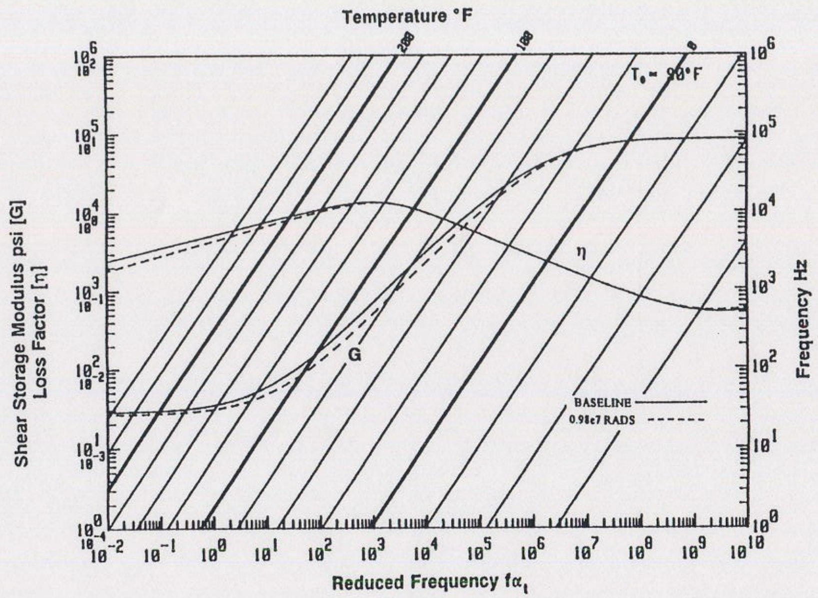

Figure 10. Anatrol AN 218 Radiation Effects

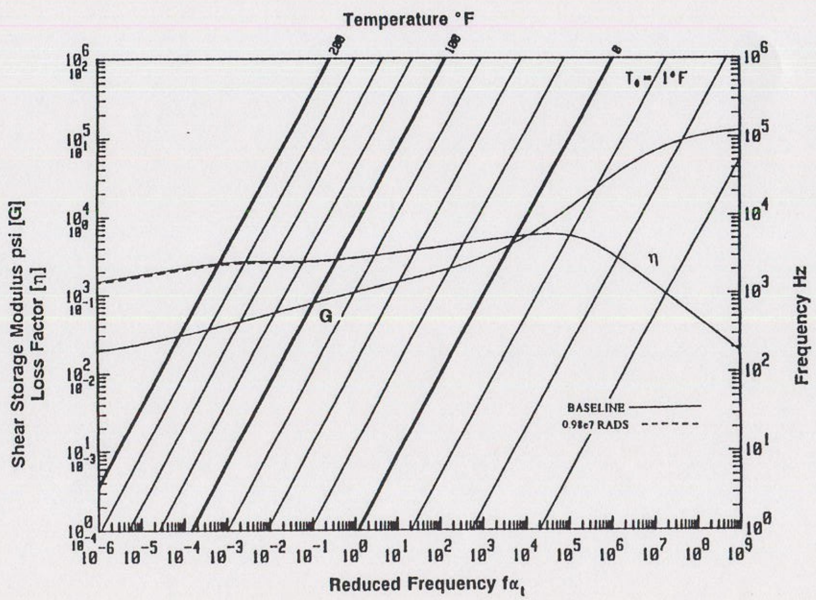

Figure 11. Furon CE 5530-C Radiation Effects

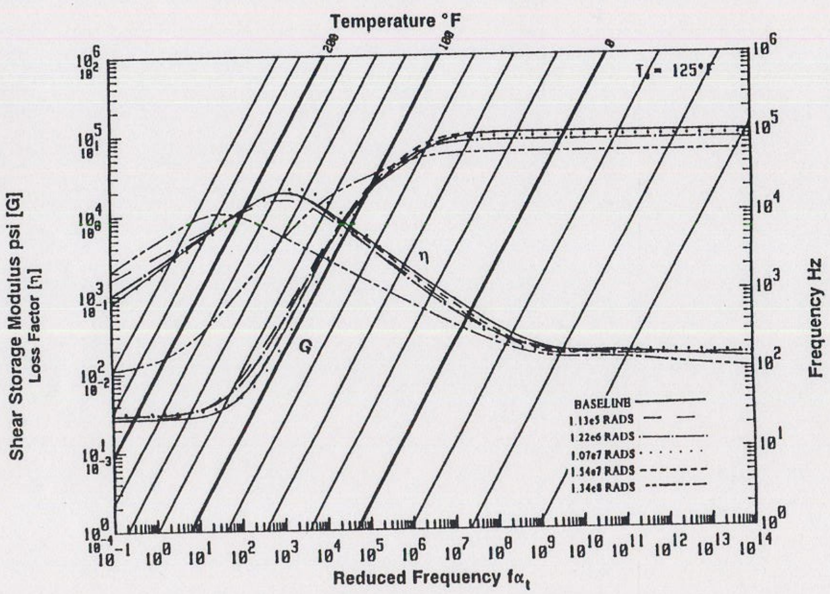

Figure 12. NORWOOD PM 220 Radiation Effects

2.4 Conclusions on radiation effects

Applications currently anticipated for viscoelastic damping materials in the APS storage ring involve radiation levels of approximately 1 x 10^4 rad/year. This is the estimated radiation environment at the top of the pedestals under the magnet support structures. Total radiation dose in these locations would be 1 x 10^6 in 100 years. Any of the damping materials tested in this program would not be significantly altered by these levels of radiation in the expected life of the facility. The results of this study are consistent with experimental measurements of magnet support structures mounted on thin PSA layers. No degradation of damping behavior was noted after the damping pads were exposed to 1 x 10^6 rad radiation. However, if other applications for these types of damping of materials are considered, where radiation doses would be greater than 1 x 10^7 rad, then the effect of radiation on the properties of these materials should be considered.

3. CREEP BEHAVIOR

3.1 Creep testing and analysis

A compression test fixture was developed by Roush Anatrol to load thin PSA layers in a manner similar to the loading conditions under the jacks of the magnet support structures. A dead weight of 127 pounds was used to load a specimen with area of 2.617 square inches with a load of 48.53 psi. An LVDT was used to measure the displacement of the specimen under load as a function of time. The test data were acquired with a Roush Anatrol data acquisition program. Post processing of data was done in MATLAB.

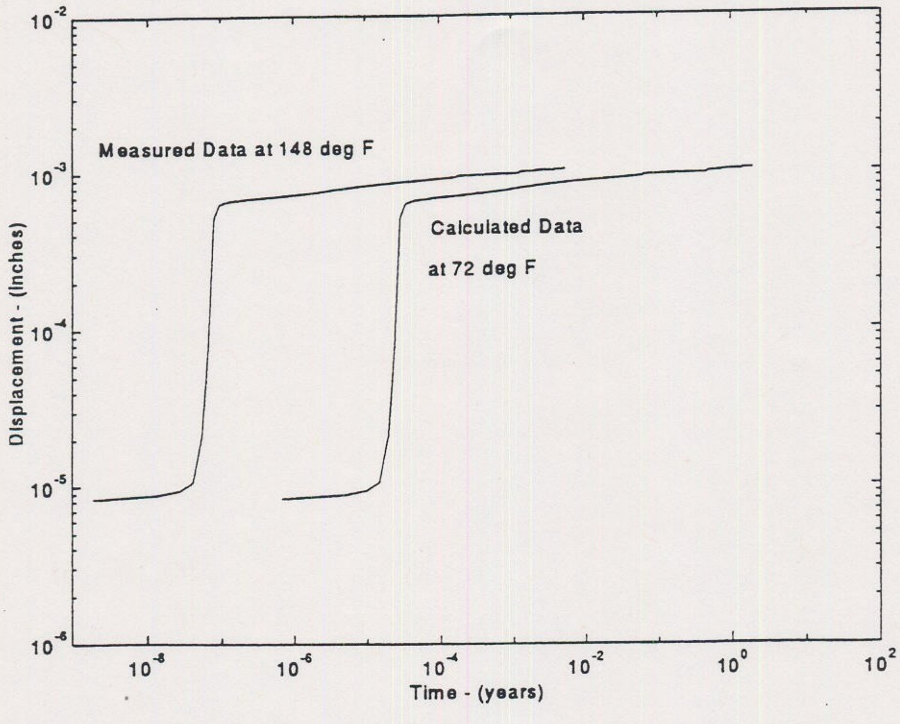

FIGURE 13: Compression creep data (148 F) - 3M ISD 112

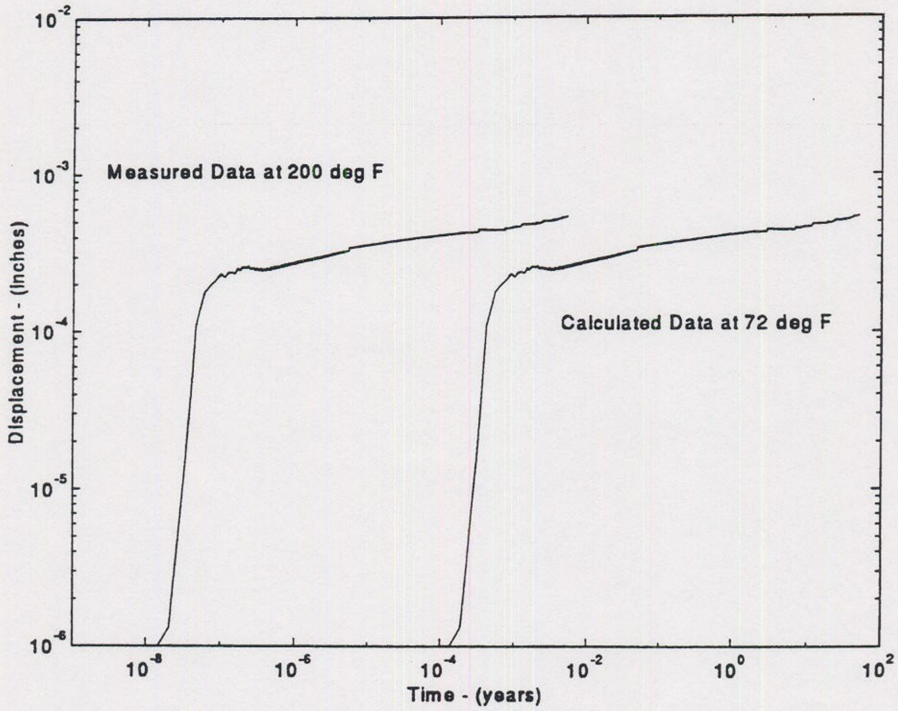

FIGURE 14: Compression creep data (200F) - 3M ISD 112

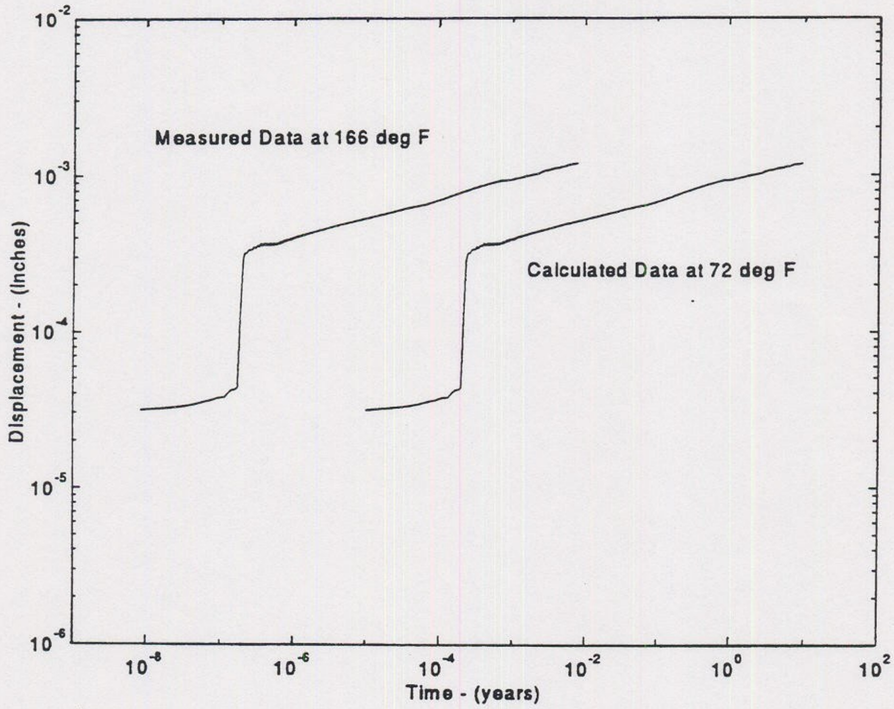

FIGURE 15: Compression creep data (166F) - Anatrol AN 217

Tests were conducted at elevated temperatures and behavior at room temperature was predicted using the time-temperature equivalence by employing a shift factor α_T [4]. This equivalence relates creep over a period of time (t) at elevated temperature to creep over a longer period of time (t/ α_T) at a lower temperature. The Arrhenius relationship has been shown to accurately model α_T for these materials [5]. This relationship for α_T is given by the equation:

$$\log \alpha_T = T_A \left(\frac{1}{T} - \frac{1}{T_0} \right)$$

where:

$\alpha_T = ShiftFactor$
$T_A = Activation\ Temperature(K) = 6000$
$T = Test\ Temperature(K)$
$T_0 = Room\ Temperature(K)$

The measured creep displacements of these specimens were greater than the displacements expected in service. This is due to effects of Poisson's stresses and the fact that the ratio of the loaded area to the unloaded area (periphery x thickness) is greater in the service geometry. If the PSA is viewed as an elastomeric spring in compression and tension, the stiffness can be estimated as[6]:

$$k = \frac{ES}{b} \kappa_T$$

where:

$E = Young's\ Modulus\ of\ the\ PSA$
$S = Cross\text{-}Sectional\ Area$
$b = Thickness\ of\ the\ PSA$
$\kappa_T = Shape\ Factor$

The shape factor is given by:

$$\kappa_T = 1 + \beta \left(\frac{S}{S'} \right)^2$$

where:

$S' = The\ nonload\text{-}carrying\ area\ of\ the\ spring$
$\beta = a\ nondimensional\ constant$
$= 2\ for\ an\ unfilled\ elastomer$
$= 1.5\ for\ a\ filled\ elastomer$

The PSA tested were considered unfilled elastomers in these calculations.

3.2 Creep results

Materials tested in this investigation included two acrylic PSA: 3M-ISD 112, and Anatrol 217. Table 1 is a summary of creep test data. Plots of measured creep displacements and calculated creep displacements for the test specimens at 72F (22.2 C) are shown in figures 13-15.

TABLE 1
Summary of Compression Creep Test Data

Material	Thickness (in)	Loaded Area, S (in^2)	Unloaded Area, S' (in^2)	Shape Factor, K_T	Test Temp (F)	Creep Displ. (10^{-3} in)	Time @ 72F (Years)
Anatrol 217	0.0066	2.617	0.0585	4003	166	0.90	10
3M ISD 112	0.005	2.617	0.04425	6996	148	0.17	2
3M ISD 112	0.005	2.617	0.04425	6996	200	0.30	10

The shape factors for the configurations used in the storage ring, as shown in figure 2, are tabulated in Table 2. These shape factors are approximately 40 . Therefore, the stiffness of the damping pad PSA layers subjected to compressive loads will be about 40 times the stiffness of the creep specimens. Creep displacements of either of these PSA layers in service can be expected to be less than 27.5×10^{-6} inches over a period of ten years. Since the damping pad has two PSA layers in series, the total creep displacement of a pad would be twice that of a single PSA layer, or less than 55×10^{-6} inches in ten years.

TABLE 2
Shape Factors for Each PSA Layer in Damping Pads

PSA Thickness (in)	Loaded Area (in^2)	Unloaded Area (in^2)	Shape Factor, K_T
0.005	100.56	0.2698	277837
0.006	100.56	0.3238	192899
0.0066	100.56	0.3562	159403

3.3 Creep conclusions

Both of the PSA tested in this effort displayed more than adequate resistance to creep for the loading and geometries considered for the magnet support structures. Dimensional stability of these damping treatments meets APS operational requirements. Furthermore, no significant change in damping performance due to creep deformation is anticipated. The results of this study are consistent with experimental measurements of magnet support structures mounted on thin PSA layers. No degradation of damping behavior was noted after several weeks of compressive loading on the PSA layers.

4. ACKNOWLEDGMENTS

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